Recipes for Writing Algorithms for Atmospheric Corrections and Temperature/Emissivity Separations in the Thermal Regime for a Multi-Spectral Sensor

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Contents

Atmospheric corrections:

- In the visible uses dark targets (vegetation, water)
- In the thermal:
  - Global Data Assimilation System (GDAS) data for atmosphere (ASTER) If the atmospheric temperature and water vapor profile is known the measured radiances can be corrected for path radiance and attenuation
  - Atmospheric retrievals from sounding channels (e.g. MODIS and ASTER) Special sounding channels provide means of measuring the atmospheric temperature and water vapor profiles directly
  - "Robust water temperature retrievals" (e.g. ATSR, MTI). "Robust" means the retrieval minimizes the influence of the atmosphere.
  - "Physics based water temperature retrievals" (e.g. MTI) "Physics based" means that we solve physics based equations to retrieve atmospheric parameters as well as surface temperature.

Physics based water temperature retrieval

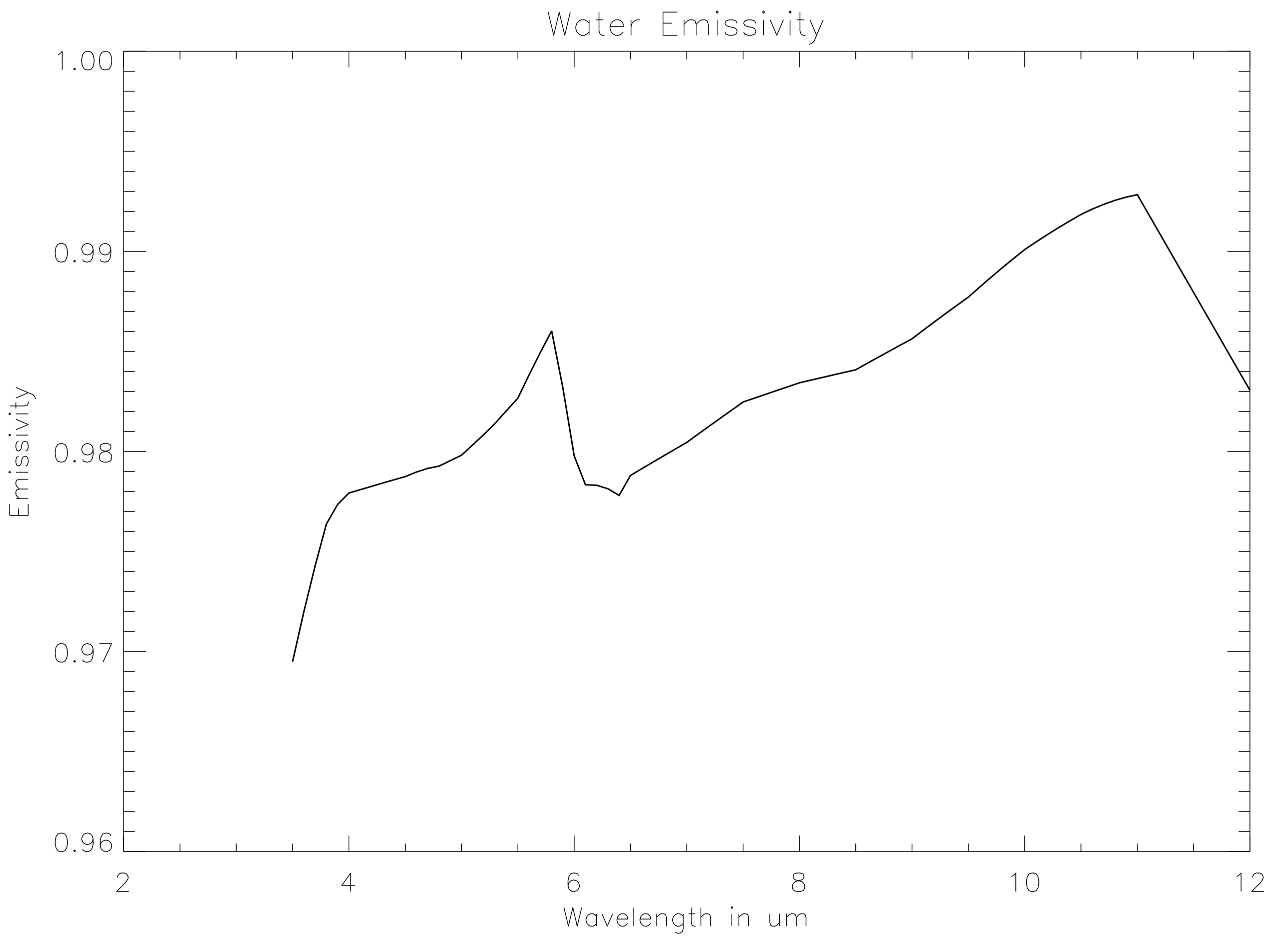
Observations:

1. The problem of temperature-emissivity separation which usually requires solving for $(N+1)$ unknowns can be simplified in the case of a known surface emissivity, such as water, to solving for the temperature only.

2. A correct solution of (1) through an atmospheric correction of the sensor radiance should lead to the **same skin temperature for all multi-spectral channels using the same atmospheric parameters.**

Note that in reality an additional atmospheric correction needs to be performed which requires knowledge of the atmospheric parameters such as columnar water vapor and atmospheric temperature.

Water emissivity model for 10 deg view zenith, 4 m/s windspeed



Currently used models: *Cox-Munk*, Monte Carlo raytracing model based on *Pierson and Moskowitz (1964), Preisendorfer and Mobley, (1986)* sea surface spectra

A simple radiative transfer model for multi-spectral sensors (1):

Measured spectral radiance $L_{m,\lambda}(H)$ along a ray reaching the sensor at height H and wavelength λ is:

$$
\begin{aligned}
L_{m,\lambda}(H) &= L_\lambda(\text{surface}) + L_\lambda(\text{path}) + L_\lambda(\text{reflected downwelling}) \qquad (1)\\
&= \varepsilon_{w,\lambda} B_\lambda(T_w)\tau_\lambda + \int_0^H B_\lambda(T_a(z))\kappa_\lambda(z)dz \\
&\quad + (1-\varepsilon_{w,\lambda})\tau_\lambda \int_H^0 B_\lambda(T_a(z))\kappa_\lambda(z)dz,
\end{aligned}
$$

where $\varepsilon_{w\lambda}$ is the water emissivity and $B_\lambda(T)$ is the Planck function in units of $W/(m^2 \mu m\ sr)$. T_w is the skin temperature and $T_a(z)$ is the atmospheric temperature profile. The atmospheric transmission is τ_λ and $\kappa_\lambda(z) = (\delta\tau_\lambda(z))/(\delta z)$.

Assumptions:

1. We neglect the reflected down-welling radiance of the atmosphere. The radiance is small in spectral bands with good atmospheric transmission and water surfaces reflect less than 3 %.

2. For simplicity we assume a one-layer model where $\kappa_\lambda(z) = \kappa_{0,\lambda} \quad \rightarrow \quad \tau_\lambda = \kappa_{0,\lambda} H$ and $T_a(z) = const$ which we'll call the effective atmospheric temperature. The path radiance can be approximated by: $L_\lambda(path) = B_\lambda(T_a)[1 - \tau_\lambda(CW)]$, where CW is the columnar water vapor amount. This approximation is quite good in atmospheric windows and its validity was tested using MODTRAN for MTI's spectral channels which lie in atmospheric window regions.

A simple radiative transfer model for multi-spectral sensors (2):

Measured spectral radiance at wavelength λ is:

$$L_{m,\lambda} = \varepsilon_{w,\lambda} B_\lambda(T_w)\tau_\lambda(CW) + B_\lambda(T_a)[1 - \tau_\lambda(CW)]. \qquad (2)$$

Solving eq(2) for the skin temperature T_w we find:

$$T_w = B_\lambda^{-1}[\frac{L_{m,\lambda} - B_\lambda(T_a)[1 - \tau_\lambda(CW)]}{\varepsilon_{w,\lambda}\tau_\lambda(CW)}], \qquad (3)$$

where the function B^{-1} is the inverse Planckian. For a multi-spectral instrument we need to integrate eq (3) over a range of wavelengths which results in:

$$T_w = B_i^{-1}[\int_{\lambda(i)_a}^{\lambda(i)_b} \frac{L_{m,\lambda} - B_\lambda(T_a)[1 - \tau_\lambda(CW)]}{\varepsilon_{w,\lambda}\tau_\lambda(CW)} d\lambda], \qquad (4)$$

where B_i^{-1} is an inverse Planckian for channel i.

Approximation of eq (4) is necessary to break the integral into two parts, one for the numerator and one for the denominator:

$$T_w \approx B_i^{-1}[\frac{L_{m,i} - \int B_\lambda(T_a)[1 - \tau_\lambda(CW) d\lambda]}{\int \varepsilon_{w,\lambda}\tau_\lambda(CW) d\lambda}]. \qquad (5)$$

Note: It is virtually impossible to eq (4) without an error for a multi-spectral sensor because we do not measure $L_{m\lambda}$!

Look-up-table generation

1. Read the spectral emissivity data ε_λ,
2. Read the spectral response data $R_\lambda(i)$ for all thermal channels i and normalize the integral over R_λ to unity:

$$R^*_\lambda = \frac{R_\lambda}{\int_{\lambda(i)_a}^{\lambda(i)_b} R_\lambda d\lambda},$$

3. Read the MODTRAN derived spectral transmission τ_λ,
4. Interpolate the spectral emissivity to the same wavelength grid as the transmission,
5. Numerically integrate the products over each filter band i for a columnar water vapor amount CW:
   (a) where the average transmission in band i is:

$$\tau_i(CW) = \int_{\lambda(i)_a}^{\lambda(i)_b} R^*_\lambda \tau_\lambda(CW) d\lambda,$$

   (b) where the average of emissivity times transmission in band i is:

$$(\varepsilon\tau)_i(CW) = \int_{\lambda(i)_a}^{\lambda(i)_b} R^*_\lambda \varepsilon_\lambda \tau_\lambda(CW) d\lambda,$$

6. Store $\tau_i(CW)$ and $(\varepsilon\tau)_i(CW)$ in a table which can be read quickly.

Finding the optimum water temperature

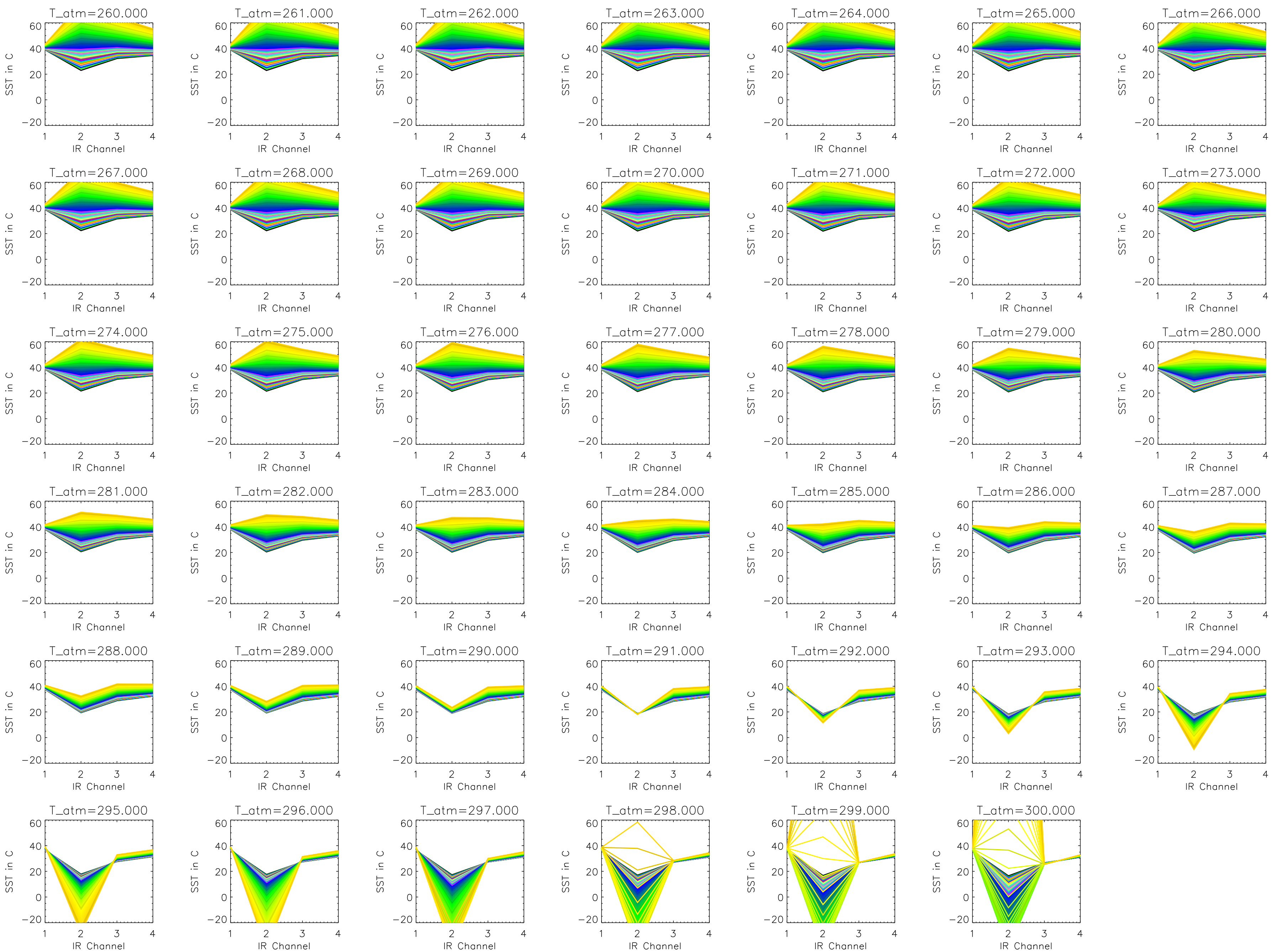
Steps:

1. Find a pixel with water in the image.
2. For a selected atmosphere k (e.g. mid-latitude winter, US standard, ...):
   (a) Compute the estimated water temperature in channel i using:

   $$\hat{T}_w(i) = B_i^{-1}\left[\frac{L_m(i) - B_i(T_a)[1 - \tau_i(CW)]}{(\varepsilon\tau)_i(CW)}\right],$$

   over a range of CW and T_a, until the estimated water temperatures $\hat{T}_{w,i}$ are most similar, i.e. minimize the standard deviation (STDEV) for a set of spectral channels i or mathematically: $\sigma_k = STDEV(\hat{T}_{w,i}) = minimum$.

   (b) Use the columnar water amount CW_{opt} and the effective atmospheric temperature $T_{a,opt}$ which minimize $STDEV(\hat{T}_{w,i})$ for the atmospheric correction of the radiance in all other water pixels.
3. Select the standard atmosphere k which is the best fit based on the smallest standard deviation σ_k of estimated water temperatures $\hat{T}_{w,i}$.



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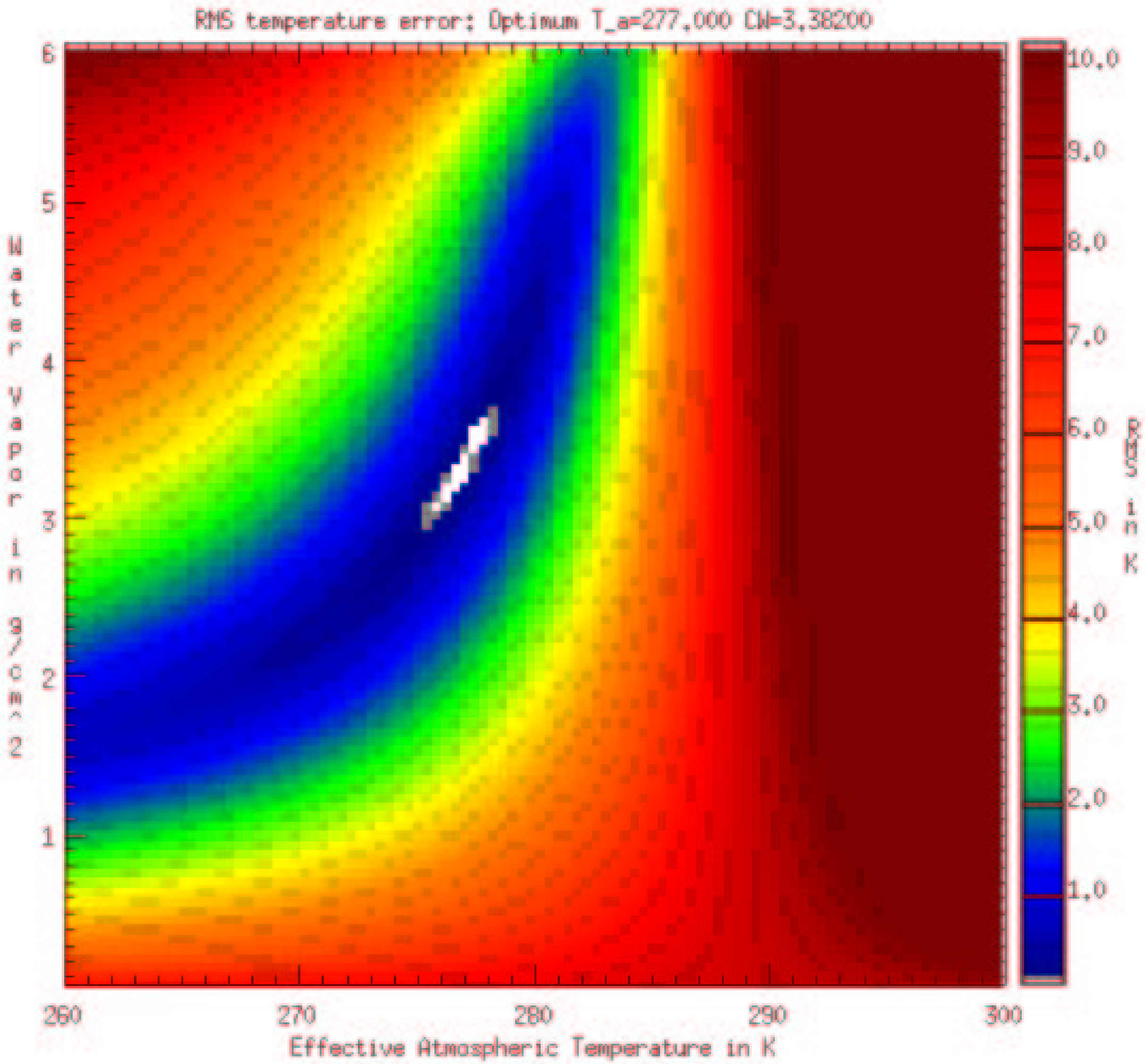
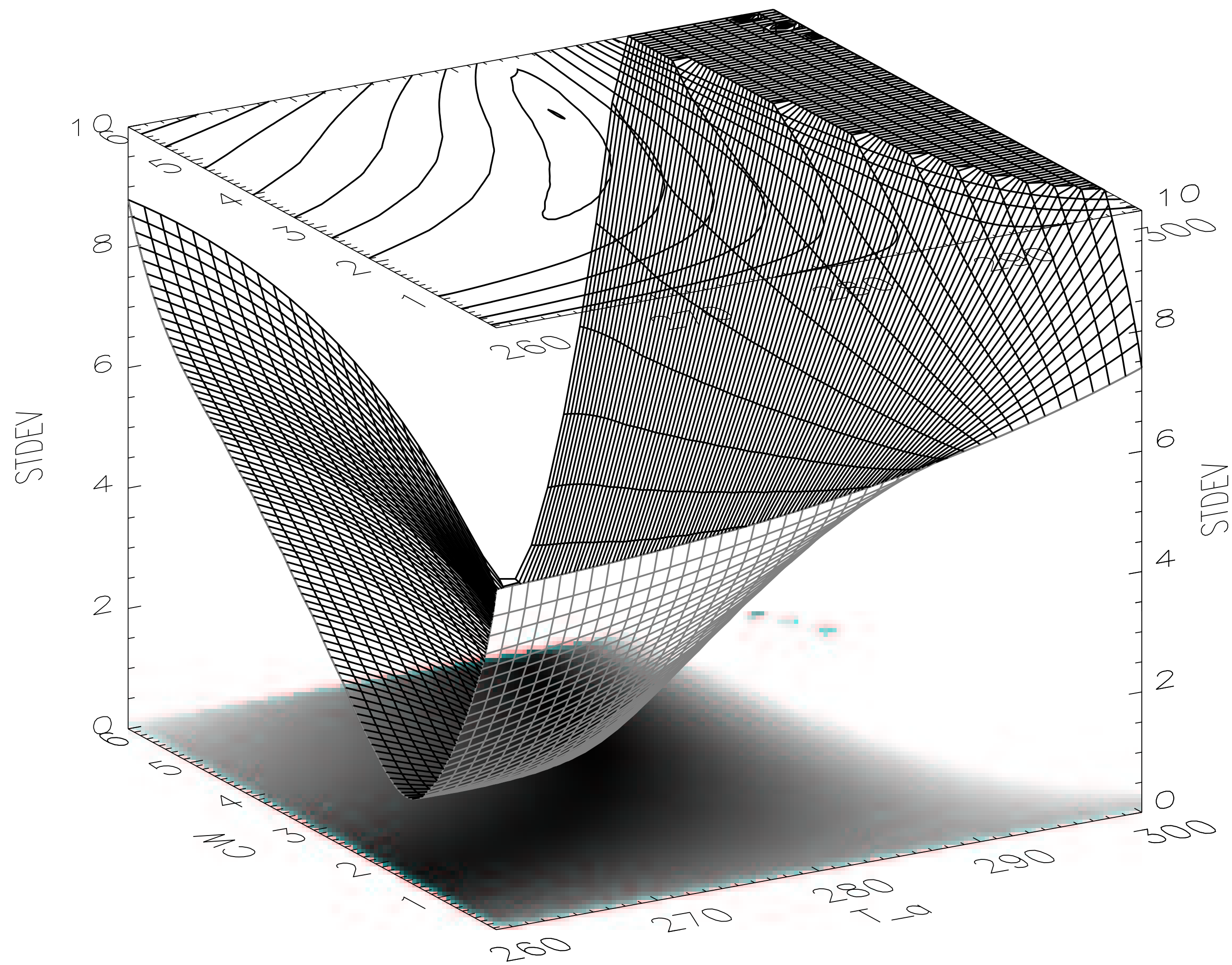
SST in C
IR Channel

Standard deviation of the retrieved temperatures for channels KLMN as a function of effective atmospheric temperature T_a and columnar water vapor CW:

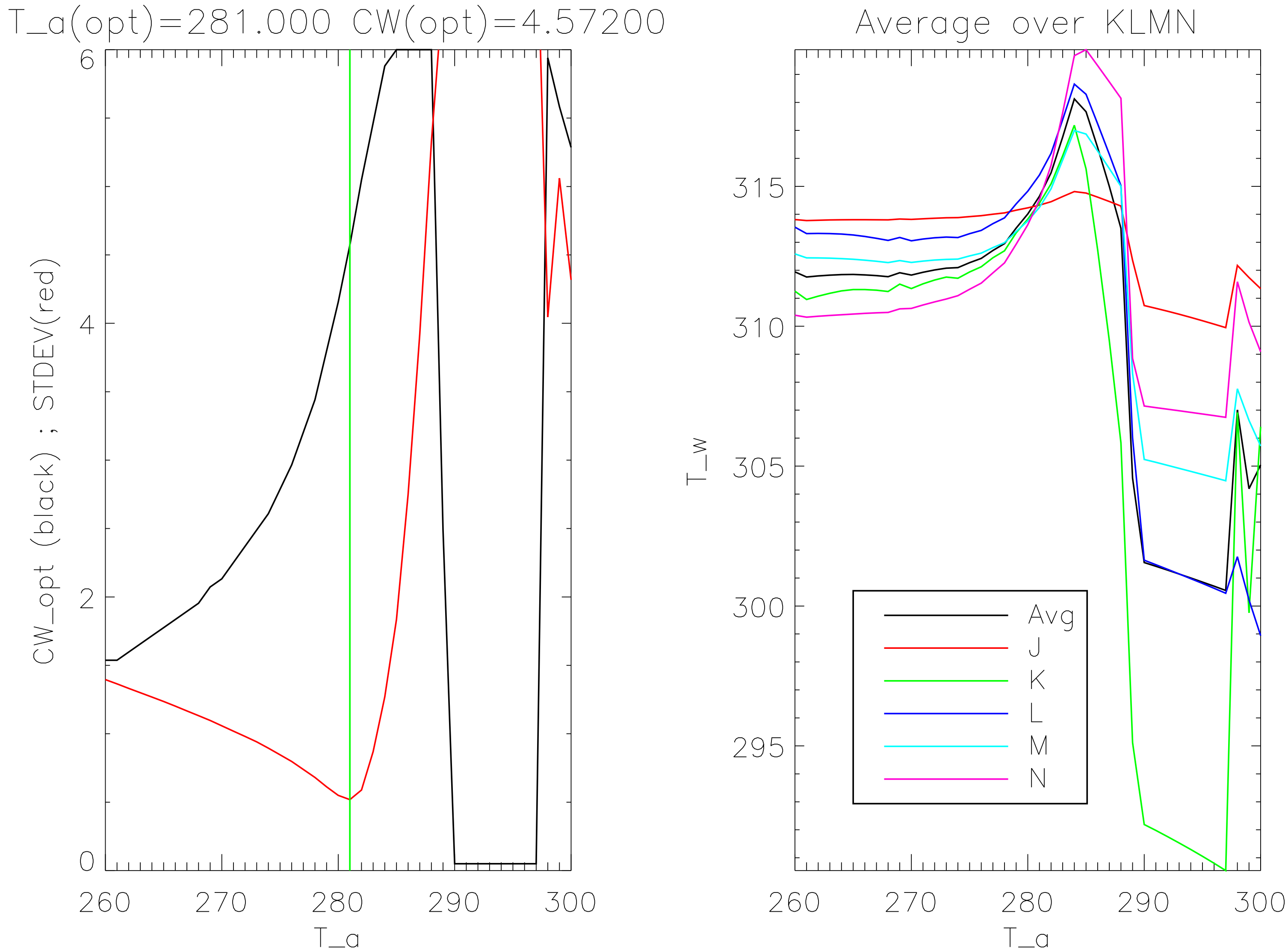


Note: White area is where $STDEV(\hat{T}_{w,i})$ is minimum.

Standard deviation of the retrieved temperatures for channels KLMN as a function of effective atmospheric temperature T_a and columnar water vapor CW:



Standard deviation of the retrieved temperatures for channels KLMN as a function of effective atmospheric temperature T_a and columnar water vapor CW:



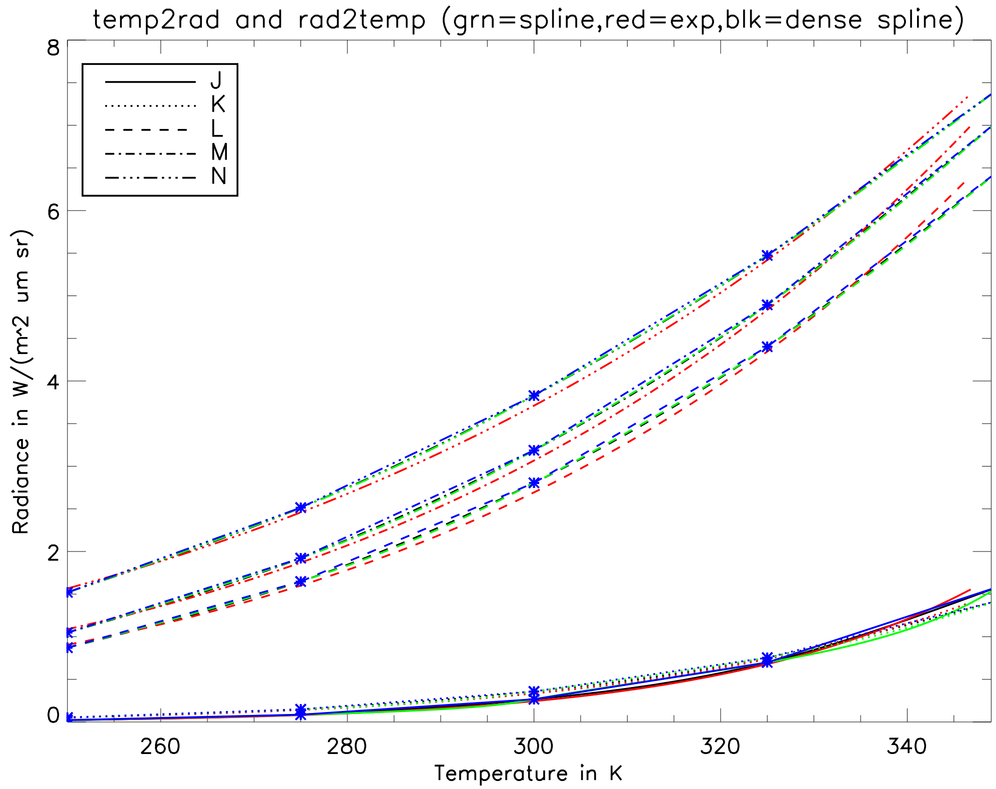
Minimum is where $STDEV() = min$ (left) and where T_w curves cross (right).

Convert from band averaged radiance to temperature and back

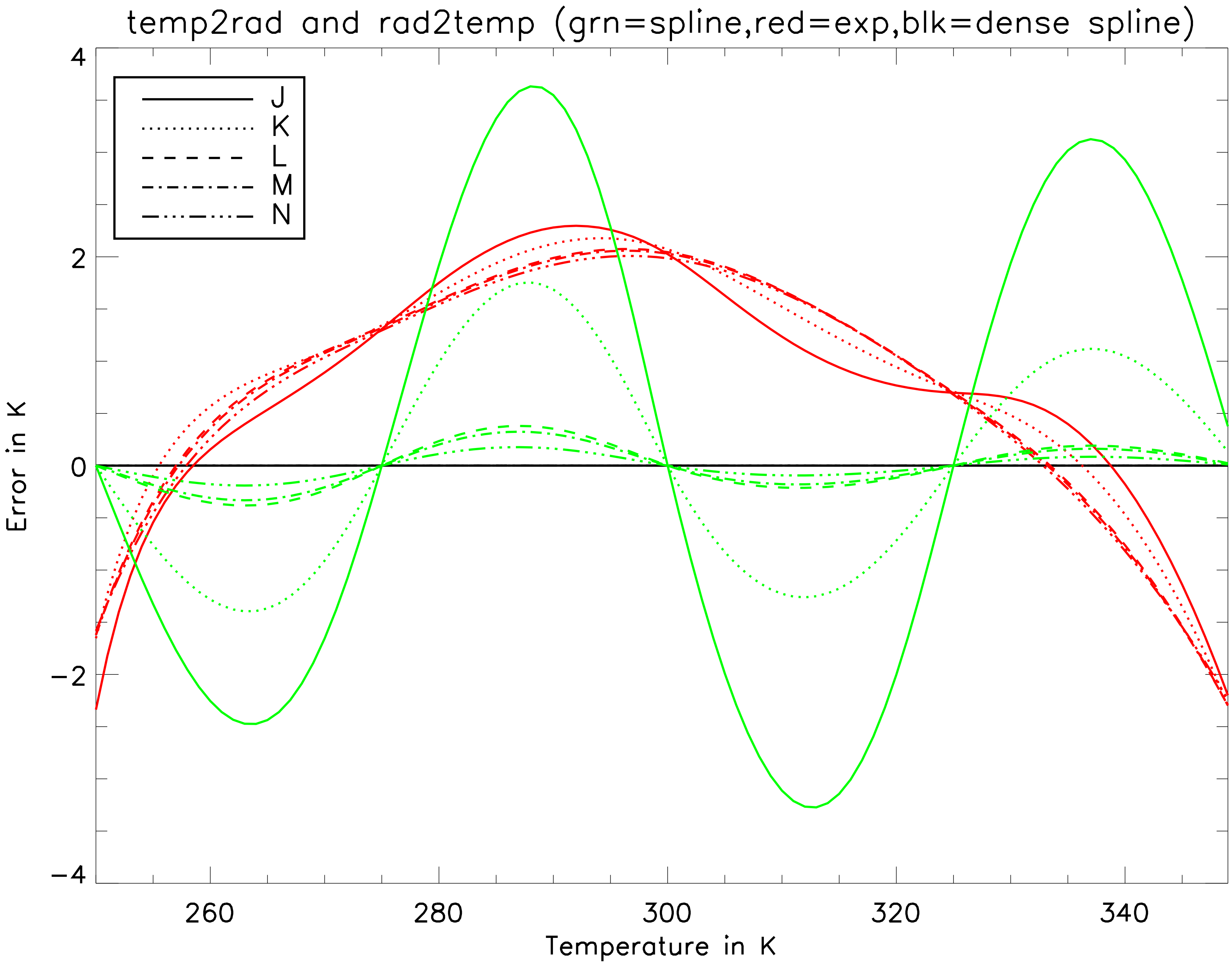
1. A quite natural way is to fit the temperature using $T(L_i) = a_i(L_i)^{b_i}$, where a_i=335.01, 335.13, 254.18, 246.34, 227.38 and b_i=0.078379, 0.10109, 0.16729, 0.17586, 0.21137. Unfortunately this method creates systematic errors of up to 2 K compared to a spline interpolation which fits each calibration point exactly.
2. Converting from x =radiance to y =temperature can be done by spline interpolation using the 5 temperatures. We found however that the spline interpolation from temperature to radiance produced large oscillations of up to 3 K amplitude in channel J, 2 K in K and less than 0.4 K for L, M and N.
3. A better approach is to first increase the number of temperatures and radiances using x =radiance and y =temperature and second perform a spline interpolation with x =temperature and y =radiance. This will result in negligible temperature errors going from radiance to temperature and back.

Band average radiance in $W/(m^2\ \mu m\ sr)$ as a function of spectral channel and blackbody temperature

Blackbody temperature in K					
Channel	250.000	275.000	300.000	325.000	350.000
J (3.5-4.1 μm)	0.0396812	0.160335	0.499058	1.30691	2.98686
K (4.87-5.07 μm)	0.356723	1.02618	2.47562	5.21626	9.88215
L (8-8.4 μm	2.88580	5.45944	9.29222	14.5840	21.4777
M (8.4-8.85 μm)	3.16871	5.80950	9.63493	14.7947	21.3864
N (10.2-10.7 μm)	3.88588	6.42711	9.78808	13.9924	19.0352



Errors made by sparse and inaccurate fitting of table:

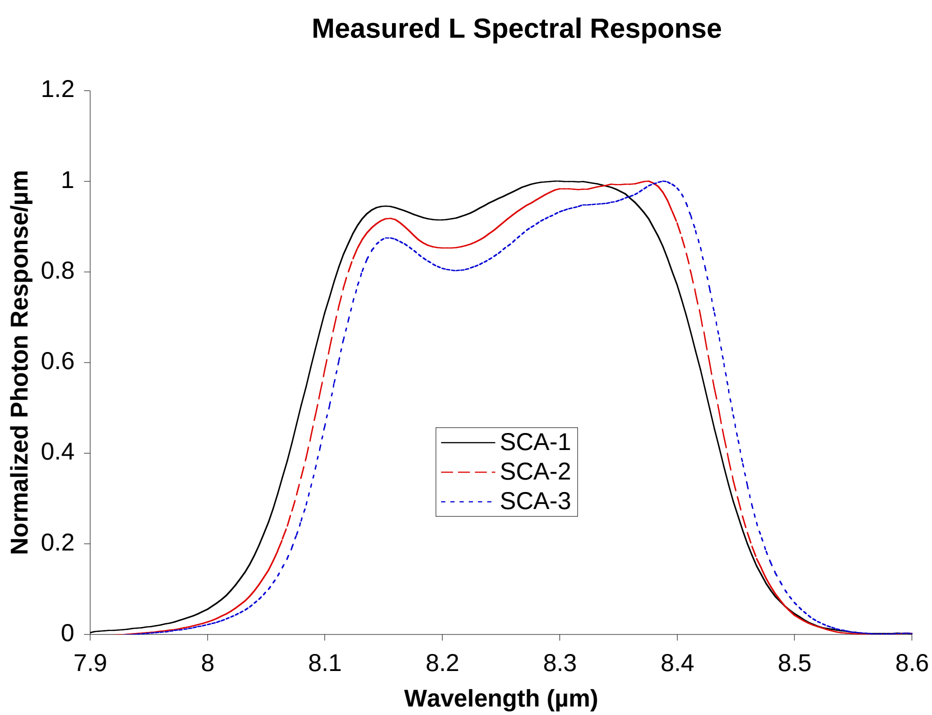


Effect of spectral shifts on atmospheric transmission

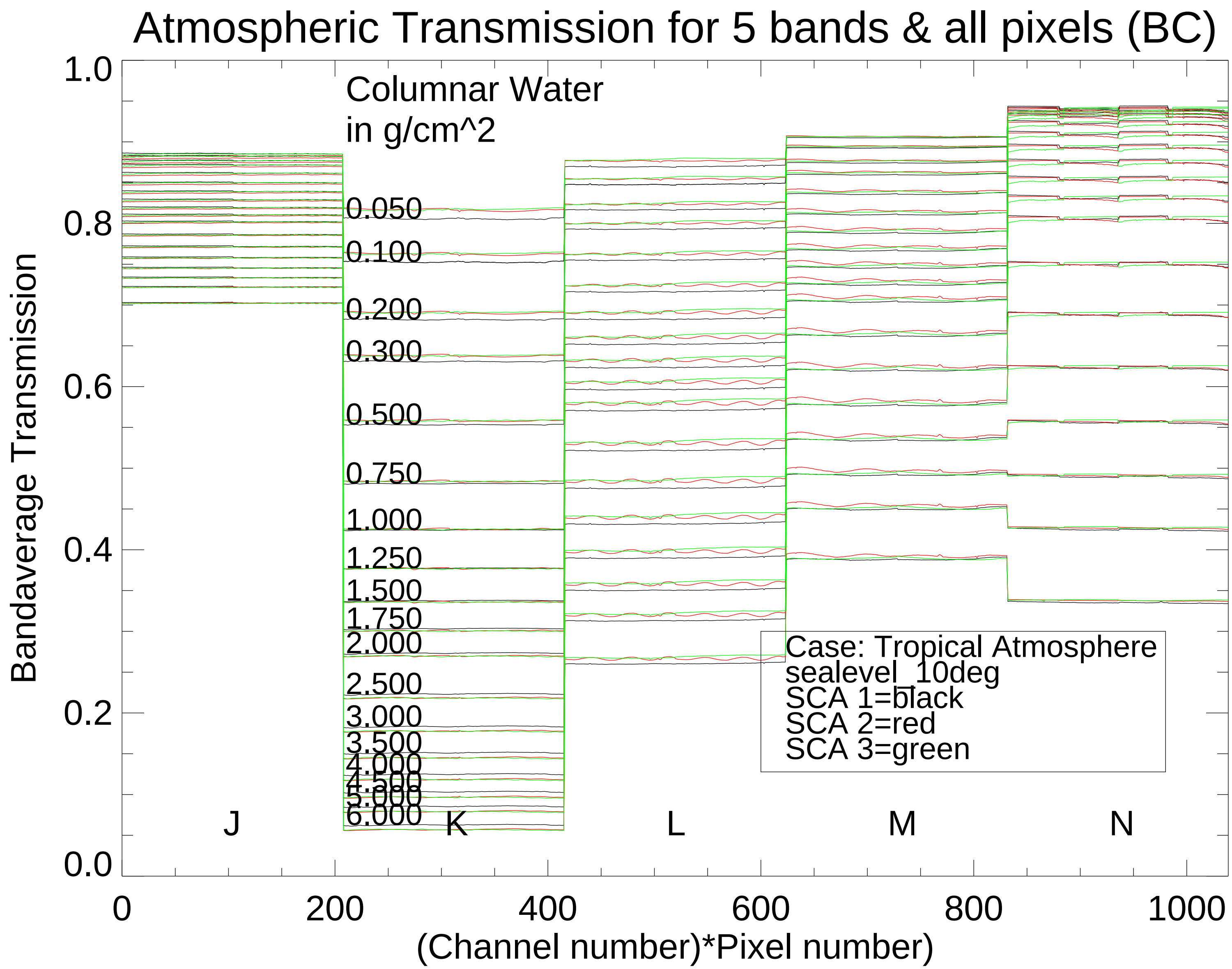
MTI's ground radiometric calibration based on:

- Filter functions measured at room temperature at nadir incidence
- Converted to pixel dependent filter functions at the actual incidence angles for a cone of light from a $f3.5$ optical system at 75 K

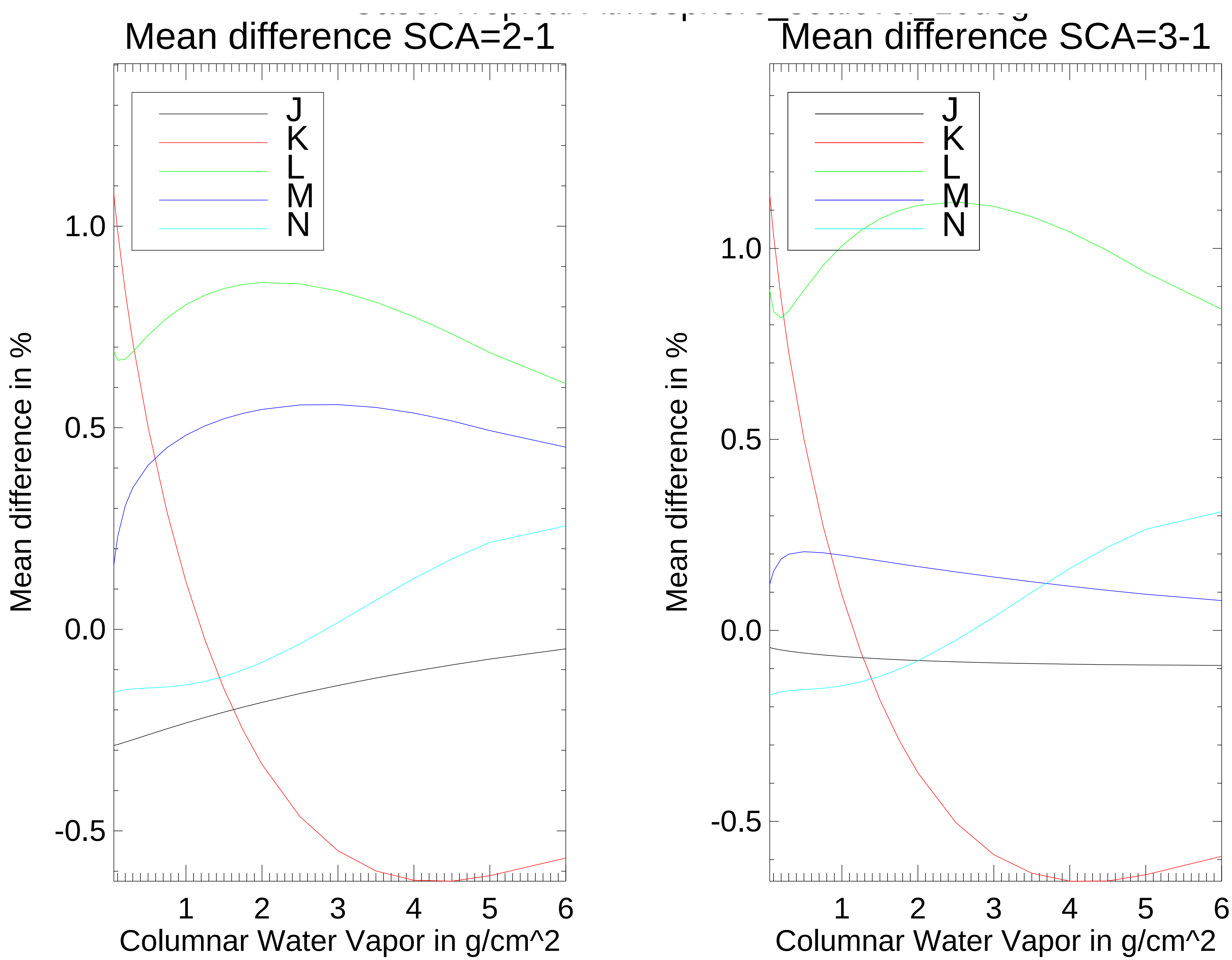
Average spectral response for sub-chip assemblies 1, 2 and 3 for channel L:



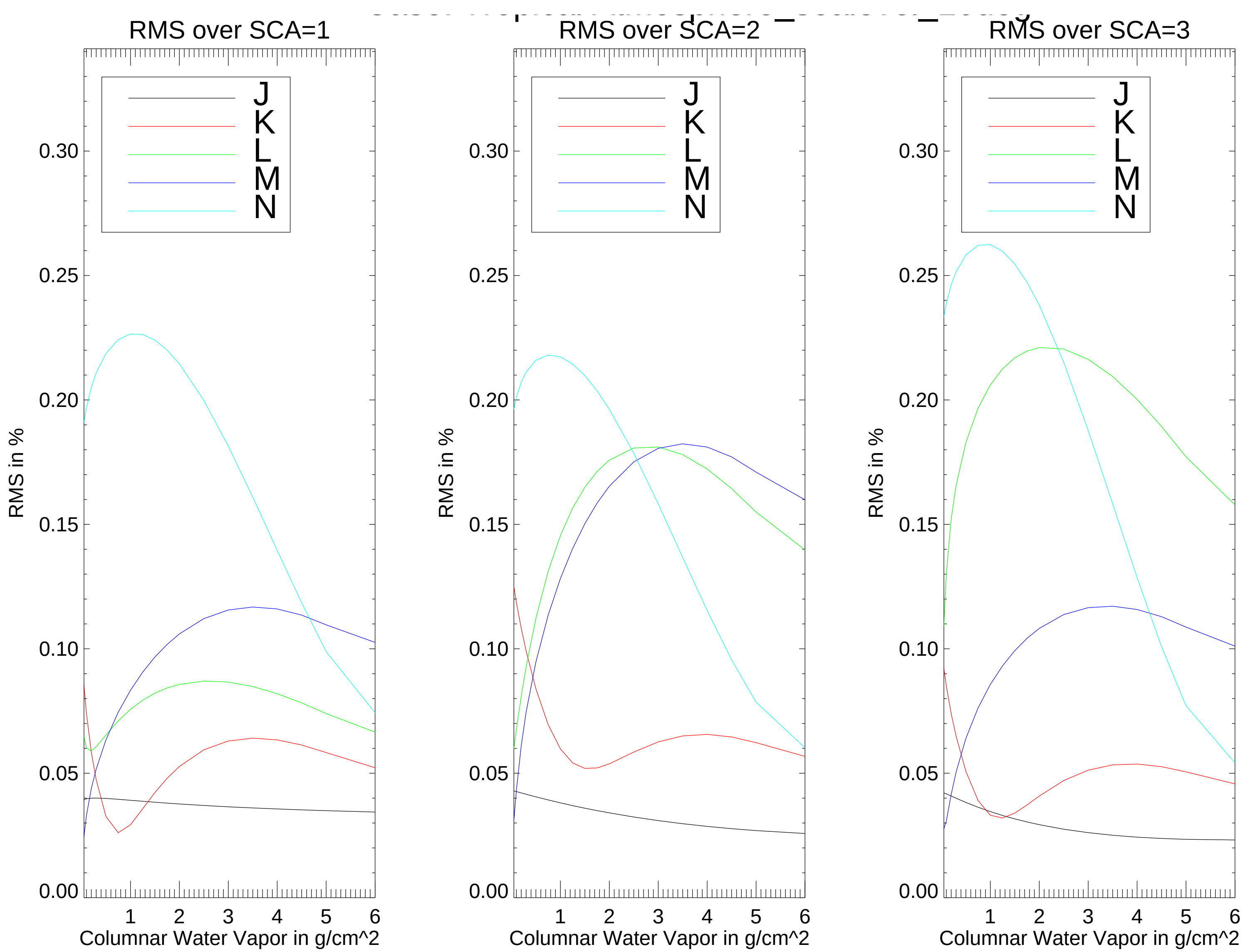
Atmospheric transmission for each pixel as a function of water vapor:



Atmospheric transmission difference between SCA's as a function of water vapor:



RMS of transmission within a SCA as a function of water vapor:



Note: Interferences within SCA's cause a ripple of up to 0.25 %

Recipe for a temperature/emissivity separation algorithm

Assumptions:

1. The multi-spectral instrument has a channel j for which most emissivities reach a similar level, e.g. around 11.5 μm many natural surfaces have emissivities between 0.95 and 0.97 (Salisbury and D'Aria, (1992)).
2. The atmosphere is homogeneous over the scene.

Algorithm:

1. Determine the atmospheric parameters over water surfaces.
2. Apply the atmospheric correction to all pixel radiances:
$$L_{c,i} = \frac{L_{m,i} - B_i(T_{a,opt})[1 - \tau_i(CW_{opt}])}{(\varepsilon\tau)_i(CW)}.$$
3. Determine the skin temperature in the channel j assuming a fixed emissivity $\varepsilon_{0,j}$:
$$T_{s,j} = B_i^{-1}[\frac{L_{c,j}}{\varepsilon_{0,j}}].$$
4. Compute the emissivities in the other channels $i \neq j$ by:
$$\varepsilon_i = \frac{L_{c,i}}{B_i(T_{s,j})}.$$

Results

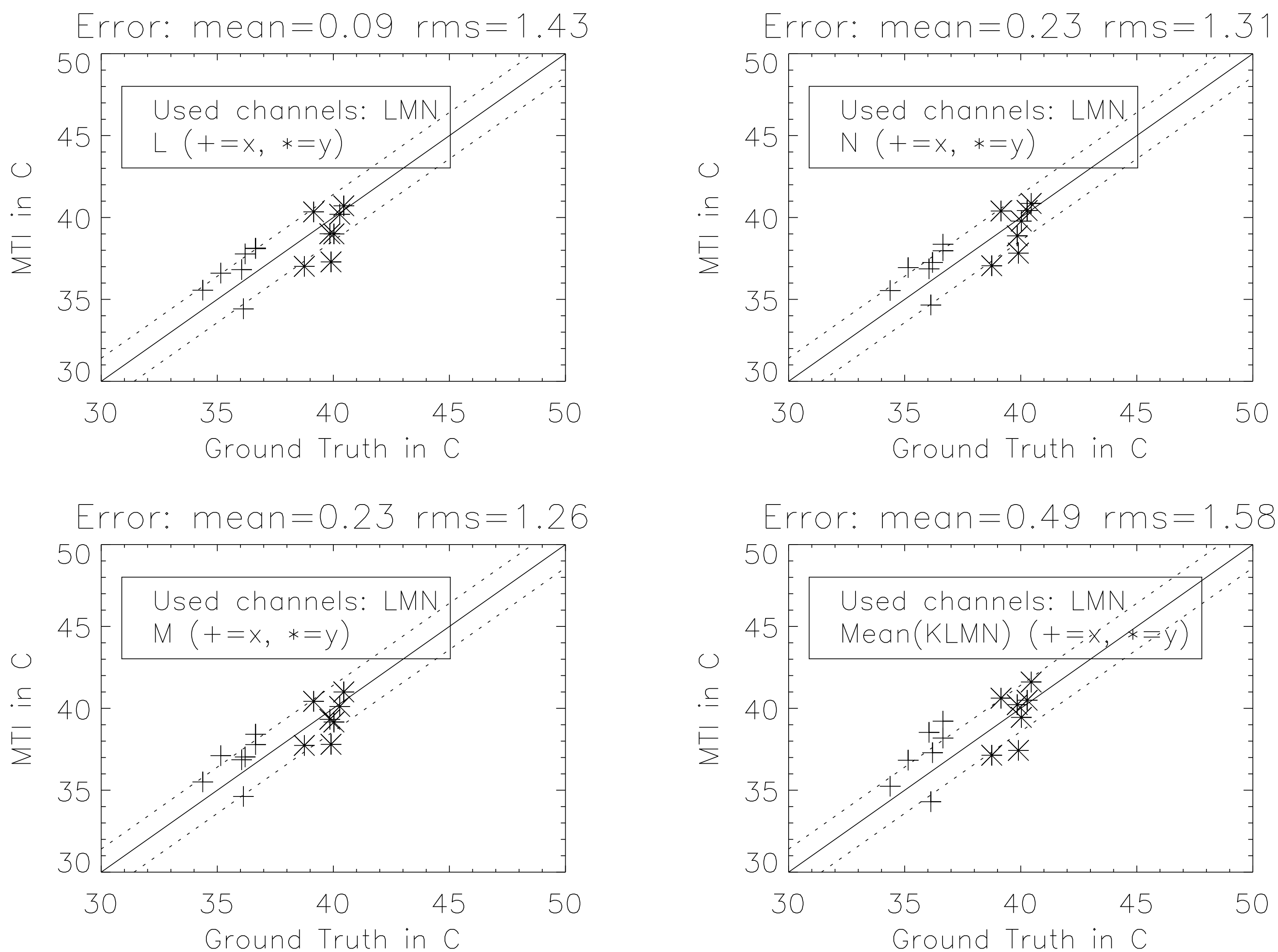
Sites:

Site A: The Squaw Creek Reservoir in Texas is located in a hot and humid area where the bulk water temperatures range from 34^o to 40^o C during the observation period.

Site B: The Crater Lake in Oregon which is a very deep lake (600 m) at 1800 m altitude with temperatures ranging from 5^o to 17^o C over the observation period.

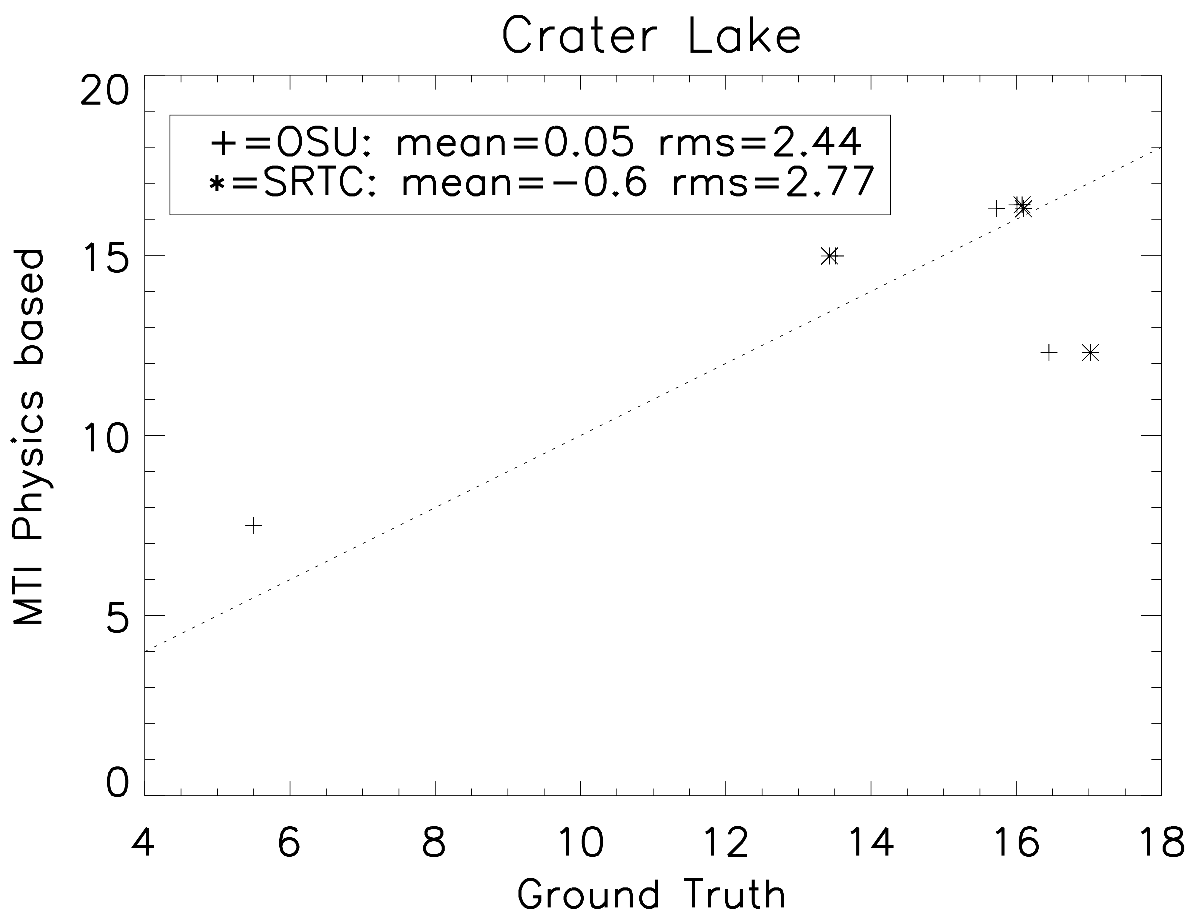
Both locations had precision sensors in place to measure the bulk water temperature.

Scatter plots with retrieved skin water temperature versus measured bulk water temperature for 2 sensor locations x and y and site A.



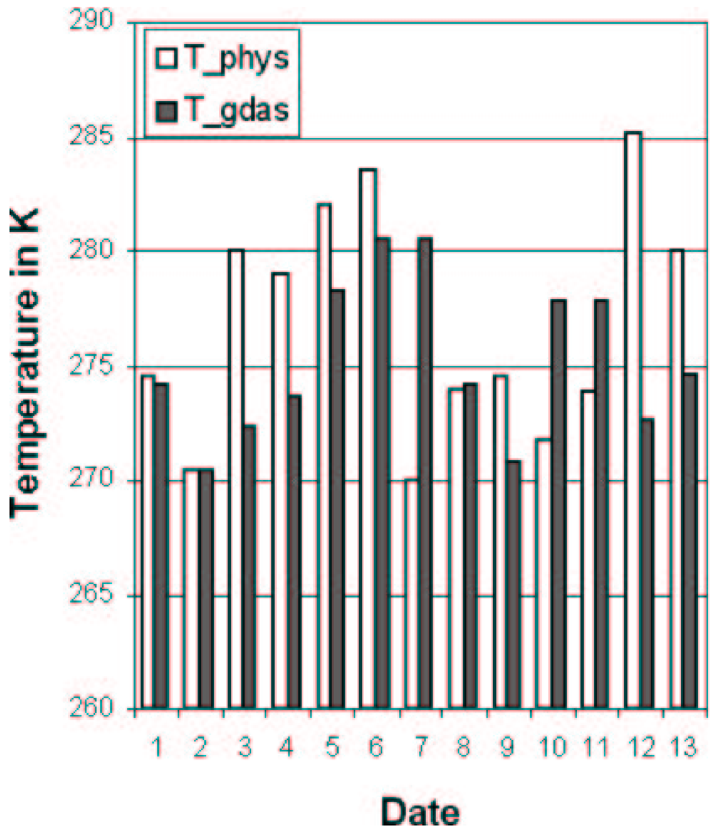
Best channel combination is LMN with rms=1.26 K

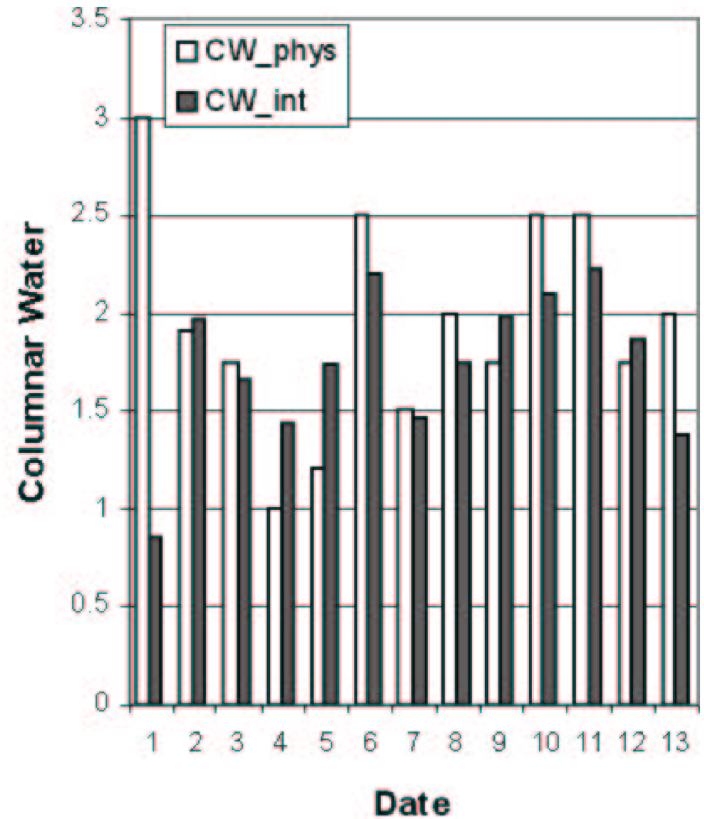
Crater lake site:



- The mean difference to MTI retrievals was 0.05 K for OSU data and -0.66 K for SRTC data.
- The variance to MTI retrievals was 2.44 K for OSU and 2.72 K for SRTC.

Comparison of retrieved atmospheric parameters with GDAS





- $RMSE(T_a(phys) - T_a(gdas))$ is 5.06 K
- $RMSE(PW(phys - PW(gdas) = 1.21$ for the water vapor

Conclusions

- Method described in Borel et al, 1999 works for actual MTI data!
- Absolute temperature error is larger than predicted but probably due to small spectra filter shifts.
- Physics based retrievals of water temperatures is accurate to within +/-1.5 to 2 K.
- Retrieved atmospheric parameters seem reasonable compared with GDAS.

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- Savannah River Technological Center, and
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